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Weed Control and the Use of Herbicides in Sesame Production

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1. Introduction

Sesame (*Sesamum indicum* L.) is one of the oldest crops known to humans. There are archeological remnants of sesame dating to 5,500 BC in the Harappa Valley in the Indian subcontinent (Bedigian & Harlan, 1986). Assyrian tablets from 4,300 BC in a British museum described how the gods ate bread and drank sesame wine together before battles to restore order to the universe (Weiss, 1971). Most people remember the words "Open sesame" from Ali Baba and the 40 Thieves to open a cave full of riches. It is similar to the sesame capsules because their opening produced great riches. Sesame was a major oilseed in the ancient world because of its ease of extraction, great stability, and drought resistance. In India today, almost as in the olden days, a farmer can take his crop to an expeller that consists of grinding mortar and pestle stones driven by a bullock. He can place the oil in a vessel, take it back to his home and have cooking oil for a year without the oil going rancid (S.S. Rajan, personal communication).

Sesame is a survivor crop. It has been planted for over 7,500 years in Asia and Africa in very poor growing conditions. In parts of Thailand, farmers broadcast the seed and came back at the end of the season and see which plant had won – the sesame or the weeds (W. Wongyai, personal communication). More often than not, the sesame won. Sesame cultivars in those areas were tall, had very long internodes, and grew above the weeds. In Rajasthan, India, sesame is the last crop that can be grown adjacent to the deserts under extreme dry conditions. In several droughts in the U.S., sesame was the only crop that survived without irrigation (Langham & Wiemers, 2002).

Although this chapter draws from research from many countries, the emphasis is on herbicides in the U.S., the only country where sesame is completely mechanized and where herbicides are critical for economic production. Sesame was introduced to the U.S. from Africa and was called beni/benne/benni. Betts (1999) quotes letters from Thomas Jefferson that document his trials with sesame between 1808 and 1824. Jefferson stated that sesame "…is among the most valuable acquisitions our country has ever made. … I do not believe before that there existed so perfect a substitute for olive oil." He talks about the rule of thumb that still exists today - that sesame will do well where cotton (*Gossypium hirsutum* L.) does well. Sesame was produced in Texas on a limited scale during the 1950's and early 1960's, first in northeast Texas and later shifting to the High Plains, where consistent yield increases resulted from irrigation and more favorable climate conditions (Brigham & Young, 1982). The sesame was cut with a binder, hand shocked, and manually fed into a combine when dry. Due to a change in guest worker laws in the mid 1960's, the hand labor from Mexico became unavailable, and the sesame crop disappeared (Langham & Wiemers, 2002). Sesame returned to Texas in 1987 with varieties that did not require binding and shocking. The sesame could be swathed into a windrow, allowed to dry, and picked up with a pick-up attachment on a combine. Since that time, new varieties have been developed that can be left standing in the field to dry down, and then combined directly. Today, sesame has spread from Texas to parts of Oklahoma and southern Kansas.

One of the more difficult problems in planting sesame is that the seeds are small and need to be placed at precise depths and densities (Langham, 2007). Seeds cannot be planted too deep that the cotyledons never reach the surface, and yet they cannot be planted too shallow that the moisture around the seed is lost to evaporation. Once the cotyledons emerge, which are small compared to other crops, the sesame plants do not grow very fast. This slow growth and development is compounded by its drought resistance because sesame will partition a large portion of photosynthetic resources to create more root mass to penetrate the soil to find moisture. In the first 30 days, sesame plants reach about 28 cm in height; however, sesame will double to 60 cm in the next 11 days, triple to 90 cm in the following 8 days, and quadruple to 120 cm in the following 9 days. Depending on row spacing and phenotype, mechanization of sesame requires careful weed management for the first 30 to 60 days after planting (Langham, 2007).

The presence of weeds can negatively influence sesame yields. Kropff and Spitters (1991) reported that the major factor influencing sesame yield in a competitive situation is the ratio between the relative leaf area of the weed and the crop at the time of crop canopy closure. The effects of weeds on sesame establishment and growth have been well-documented. Balyan (1993), Gurnah (1974), Singh et al., (1992), and Upadhyay (1985) reported weed-induced reductions of sesame yield up to 65% and a need for a critical weed-free period up to 50 days after planting. Under weedy conditions, Eagleton et al., (1987) recorded a weed biomass six times that of sesame 48 days after planting and Bennett (1993) reported a weed biomass 1.3 fold that of sesame 42 days after planting. Without an herbicide, hundreds of hectares have been disced under in the U.S. due to excessive weed pressure.

Mechanically harvested non-dehiscent varieties present another problem that is not present in manual harvest, which comprises 99% of all sesame harvested in the world (Langham & Wiemers, 2002). If there are weeds in manual harvest, only the sesame plants are cut and placed in the shocks. However, in mechanical harvest, sesame and weeds are cut together. In Venezuela, a binder cuts the sesame and weeds together while they are still green, which is not a problem because the weeds dry down at the same time as the sesame. The only concern is that a high population of weeds may delay the combining because weeds may envelop plants and trap moisture or thicker stem weeds such as pigweed (*Amaranthus* spp.) will take longer to dry down. In direct combining, the weeds can be a big problem because they are normally green and add moisture to the combine bin. There are many cases where the sesame seeds are dry and weed seeds are not. Thick weed stems can add moisture, but the major problem is weed seeds. Since it is logistically difficult to scalp off the weed seeds at harvest, moisture from the weeds will transfer to sesame seeds. Sesame is 50% oil and needs to be harvested at 6% moisture or below in order to be transported by trucks and stored in silos. High moisture under these conditions can lead to heating and ruining of the seed. A second concern is that mechanically harvested sesame moves through a series of augers from the combine screen, to the combine bin, to the grain buggy, to the truck, to the silo, to the cleaning equipment, and within the cleaning process. Moist sesame can be damaged by this movement forming free fatty acids and leading to spoiling (Langham & Wiemers, 2002).

The small size of the sesame seed is similar to the size of many weed seeds (Langham, 2008; Langham et al., 2010). When sesame is used for oil, weed seeds within the sesame samples are not as critical unless they are toxic. However, a large percentage of sesame is used in the edible markets that require 99.99% purity. There are seeds such as johnsongrass [*Sorghum halepense* (L.) Pers] and other grass seeds that would seemingly be easy to remove because of their size and shape; however, these seeds go through the round holes of the cleaning screens end first and are difficult to separate in gravity tables because they have a similar specific gravity to sesame (Langham, 2008). In decortication of the seed for bakery products and tahini, the seed from lanceleaf sage (*Salvia reflexa* Hornem.) can cause a unique problem. When the lanceleaf sage seed has been hydrated, the seed surface formed a gelatinous substance that can cause all the sesame seeds around it to stick and form balls. Kochia [*Kochia scoparia* (L.) Schrad], buffalobur (*Solanum rostratum* Dunal), Russian thistle (*Salsola iberica* (Sennen & Pau) Botsch. ex Czerep.), tickseed also known as bugseed (*Corispermum hyssopifolium Nutt.*), and several species of grass seeds are other weeds that are difficult to separate from sesame. Any weed seed that is in a sesame sample in a large percentage is difficult to separate out, no matter the size and specific gravity, without having to slow down the processing or reprocessing. In Japan, purity needs to be 100% since processors have to pay claims to customers that find anything other than pure sesame seeds (author's personal observation).

Broadleaf weeds such as morningglory (*Ipomoea* spp.) and smellmelon (*Cucumis melo* L.) affect sesame growth and development. These weeds come up in flushes after a rainfall or irrigation event and after sesame canopy formation (Grichar et al., 2001a; Grichar et al., 2009). They can continue growing under weak light conditions, climb the sesame plants to the top of the canopy, and when they reach the light, greatly expand their infestation. As soon as they reach light, their leaf size increases dramatically. In high populations, these climbing weeds form a mat on top of the sesame and cause problems at harvest because it is difficult to separate adjacent rows of sesame (Langham et al., 2010). Many farmers go into these areas and treat with a herbicide such as glyphosate and sacrifice the sesame to keep the weeds from producing seeds and increasing the problem in future years. In general, annual plants are more susceptible to glyphosate than are perennial plants containing well-established underground propagules (Akin and Shaw, 2004). This difference in susceptibility is primarily due to the ratio of herbicide-intercepting foliage compared with the number of active sinks that need to be inhibited for plant death to occur (Franz et al., 1997). Successful control of perennial weeds with foliar-applied herbicides depends on the rapid absorption and basipetal translocation of the biologically active compound (e.g., glyphosate) into the underground storage organs in sufficient quantities to kill the entire plant before metabolism can degrade the compound (Sprankle et al., 1975).

Sesame is mainly grown in countries where abundant and inexpensive labor is available (Schrodter & Rawson, 1984). However, the trend in agriculture around the world is towards mechanization. Sesame has disappeared in Japan and parts of Mexico as the sesame growing areas mechanized. In Korea, sesame hectares have continually decreased since 1987 as the labor migrates to the cities (C. Kang, personal communication). With weak seedling vigor, limited competitive ability, and a lack of cheap labor, the use of herbicides are essential for commercial mechanized sesame production.

There has been considerable progress in mechanizing the crop by the development of non-dehiscent capsules (Langham & Wiemers, 2002) that hold the seed until combining and release the seed within the combine with minimum threshing. In addition, the growth habit of phenotypes has been changed to more readily feed into combines. The one area of best management practices for sesame that is still in development is the use of herbicides. Several agronomic practices have reduced the need for herbicides in dry areas. Preplant weed control followed by cultivation between rows has helped reduce weeds until the crop has reached a sufficient height to form a canopy. In areas that have early-season rainfall, herbicides use is essential. In addition, the trend towards minimum and no-till practices will require both preemergence and postemergence herbicides. A preemergence herbicide is applied to the soil before emergence of the specified weed or crop, whereas a postemergence herbicide is applied after emergence of the specified weed or crop (Senseman, 2007). There are two types of postemergence: over-the-top and directed application. In the latter, the herbicide is applied with a hooded sprayer with herbicide being applied between the rows and to the bottom of the crop - normally the lower 5 to 10 cm. In many areas where glyphosate tolerant crops are readily grown, there are no longer hoe crews available to manually clean the fields.

In mechanical harvest, there is an additional window of weed control that is important. The major form of weed control after the first 30 to 50 days of planting is the formation of the sesame canopy which blocks out light. At about 60 days after planting, current sesame varieties begin losing the leaves under the canopy where there is no light. As the plants mature, they self-defoliate and leaves are shed by about 100 days after planting. Without a harvest aid, it takes 40 to 50 days from the time that the plants lose all their leaves until the sesame is dry enough to combine. The leaves are a major part of the sun-blocking canopy, and as the weight of the leaves are lost, the branches become more erect, which allows more sunlight to penetrate the canopy. With autumn rains there may be new flushes of weeds, particularly fast-growing annual grasses. These late emerging weeds can be controlled in four ways: 1) applying postemergence-directed herbicides that have soil residual properties; 2) use of narrower row spacing; 3) planting the rows north/south so that there is light to the ground only at mid-day; and 4) using harvest aids to shorten the sesame drying period and which also kill and dry weeds.

Bennett (1993) found that alternating of grass and broadleaf crops in Queensland, Australia, helped in reducing weed populations since broadleaf weeds were more easily controlled in the grass crops and the grass weeds were more easily controlled in the sesame crop. However, this method is not as effective in the U.S. In many areas where either corn (*Zea mays* L.) or sorghum (*Sorghum bicolor* L.) was grown in the previous growing season, broadleaf weeds appeared late in the season and often were not controlled until after they have produced seed. Many of these problems result from the inability to disc the weeds mechanically due to lack of soil moisture. In growing wheat (*Triticum aestivum* L.) in the winter and spring prior to sesame, there are two problems: (1) there can be residues from broadleaf herbicides applied to the wheat in the spring that are toxic to sesame, and (2) there are many broadleaf weeds that will not germinate until the warm summer temperatures. In all areas, there are winter weeds that will not germinate until the sesame plants lose their leaves.

Planting sesame in fields with low weed pressure and knowledge of herbicide carryover from the previous crop to sesame are important in reducing weed competition and possible sesame injury. To date, the primary means of controlling weeds has been with cultivation. However, cultivation cannot reliably control weeds within the seed row that emerge while the sesame is emerging. Since sesame grows slowly in the first three to four weeks, many growers have waited three to four weeks to cultivate. Sesame roots follow moisture and with rain or irrigation in the first few weeks after planting, the roots may grow laterally and stay near the surface. Cultivating too close to the plant can cut roots and plants will wilt quickly and possibly die. In times of a dry season, roots grow more vertically allowing for closer cultivation. The cultivation process can throw soil up on the base of the plant covering any small weed after sesame plants are 10 to 15 cm in height. When a tractor is used for cultivation, sesame can be cultivated when it is slightly taller than the tractor axle, but it should be done in the afternoon when the plants are less turgid. Flower petals may fall, but the young capsules are rarely knocked off by the tractor (Langham et al., 2010). Breaking or creasing the main stem damages the sesame and prevents the plant from developing.

In many sesame growing areas, the trend has been to move to no-till practices excluding the use of cultivation. Most varieties used in the U.S. were developed for use on row spacing of 50 to 100 cm and were not suitable for narrow row spacing primarily because of the large leaves creating too much competition between the sesame plants. Most of the sesame grown in North and South America was bred from varieties developed by D.G. Langham in Venezuela in the 1940-50s. Without herbicides and insecticides, he found that large leaves canopied faster and outgrew many of the insects (B. Mazzani, personal communication). The current breeding programs have created potential varieties with smaller leaves that will allow for row spacing as close as 15 cm apart. With this narrow row spacing, the canopy can develop and close within 30 days of planting, which can be about the time that some preemergence herbicides are no longer effective. There is the potential to develop varieties which develop closure in 21 days, but there will always be a trade-off between too much inter-row sesame competition and rapid canopy.

Although the main thrust of this paper has been the controlling of weeds in sesame, there is always a concern as to whether sesame will become a weed in other crops used in rotation with sesame. There are many herbicides used in other crops that will prevent sesame from germinating. To date, only postemergence applications of glyphosate have consistently controlled sesame from the juvenile stage on through maturity. However, prometryn, flumioxazin, imazapic, trifloxysulfuron, mesotrione, flumetsulam, and foransulam have been effective in controlling sesame in some studies (Grichar et al., 2001a; Grichar et al., 2009). Many postemergence herbicides used in other crops will delay sesame maturity enough for the crop to canopy over-the-top of the sesame.

Until the advent of Roundup Ready® cotton, there was concern that sesame could become a problem weed in a cotton rotation. Under normal planting conditions, cotton germinates about 5 degrees cooler than sesame and has a faster growth rate in the first 30 days than sesame. Cotton planted during a normal planting window rarely will have sesame as a weed. The problem with volunteer sesame has primarily been in areas where cotton planting has been delayed due to environmental conditions or for integrated pest management. When there has been a volunteer sesame issue, most of the cotton herbicides will damage sesame, but will rarely kill it. As long as the cotton stand is good, the cotton will outgrow and canopy the sesame, but with a low cotton population, sesame would persist. However, sesame was never a problem in the harvest of the cotton.

Volunteer sesame could be a problem in groundnut (*Arachis hypogaea* L.), but with peanut herbicides such as imazapic or imazethapyr, volunteer sesame is no longer an issue. Volunteer sesame was never an issue in monocot crops such as corn, sorghum, and small grains because there are many good broadleaf herbicides that can control sesame. Theoretically, sesame could be a weed in many vegetable crops, but with a wide range of herbicides approved for those crops and the usual presence of manual labor, volunteer sesame has not been a problem in any vegetable crop to date.

2. Herbicides, weed control, and sesame tolerance

Several herbicides provide excellent control of weeds with minimal to no damage to sesame. However, in evaluating herbicides, there have been conflicting results, and it is difficult to sort out why some herbicides work in one area and do not work in another. Also, in some cases, at the same location, the herbicides effectively control weeds and little sesame injury is noted in one year; however, the opposite may be true the following year.

With most herbicides, herbicide dose, formulation, soil texture, pH, moisture, method of incorporation, and temperature before and after application are all a factors affecting herbicide persistence (Smith, 1989). Since soil organic matter, temperature, and aeration are more favorable for microbial activity in the topsoil than in the subsoil, degradation rates may decrease if a herbicide is leached into the subsoil (Smith, 1989). Soil pH can affect degradation directly if the stability of the herbicide is dependent upon acidity or alkalinity, and indirectly via its effects on the absorption of the herbicide to the soil (Smith, 1989). Increased rates of non-biological reactions and biological processes are favored by increasing temperature, herbicide degradation rates should increase also. Adequate moisture is also essential for microbiological activity (Smith, 1989). Martin (1995) reported that rainfall amounts during germination and establishment can markedly affect herbicide phytotoxicity to sesame, a possible factor in the reported erratic behavior of many herbicides. Many herbicides will delay sesame maturity while a few herbicides will completely kill the sesame. In many of the studies mentioned below, it will be seen with some herbicides that even with severe stand reduction, sesame yields are good because the plants can compensate for open space by putting out branches with capsules.

In some herbicide studies in the U.S. where multiple varieties were used, there have been differences in varietal susceptibility. Some of the clues have not been followed up because the moving baselines of new varieties has been fast, and the emphasis has always been placed on the use of the most recent released variety to use in herbicide evaluations. More work needs to be done in this area; particularly to determine whether a specific genotype may have more tolerance to a particular herbicide.

A review of sesame herbicide information from 21 countries has shown that there are approximately 16 herbicides that are used or have the potential to be used in commercial sesame production somewhere in the world (Langham et al., 2007). Some of these products are not available in the U.S. or have been discontinued. Table 1 shows the active ingredients of these 16 current herbicides that show the greatest potential for weed control in sesame production. The table does not contain herbicides such as flumioxazin that is used commercially in other parts of the world, but have resulted in considerable sesame injury in the U.S. (Grichar et al., 2001a; Grichar & Dotray, 2007).

Just as important as knowing the potential use of herbicides, it is important to note herbicides that have resulted in severe sesame injury or have had mixed results. In some cases, another application method of a herbicide in Table 2 can be toxic, e. g., glyphosate postemergence over-the-top.

Use	Preemergence	Postemergence	Postemergence-directed
Commercial	Alachlor Diuron Fluchloralin Fluometuron Glyphosate Linuron Metobromuron *S*-metolachlor Pendimethalin Trifluralin	Clethodim Diuron Fluazifop-P-butyl Sethoxydim Haloxyfop	Diuron Glyphosate (only between rows or wiper application)
Potential	Acetochlor Diuron + linuron *S*-metolachlor + diuron *S*-metolachlor + linuron	Pendimethalin *S*-metolachlor Alachlor Acetochlor	Diuron + linuron Linuron Diuron Prometryn

Table 1. Current and potential herbicides for use in sesame.

There are many preemergence herbicides that have been successfully used in sesame growing regions worldwide. These would include: alachlor, diuron, fluchloralin, fluometuron, linuron, metobromuron plus metolachlor, metolachlor, pendimethalin, and trifluralin. In the U.S., the main herbicides are *S*-metolachlor, diuron, linuron, and alachlor. Fluchloralin and metobromuron are not available in the U.S. Glyphosate is often applied with the preemergence herbicide to control emerged weeds. Herbicides act differently under certain environmental conditions which include variability in soil texture, organic matter, temperature, pH, humidity, rainfall timing and intensity, and under different methods and timing of application (Grichar et al., 2001a; 2001b). Pendimethalin and trifluralin are particularly difficult to use with results ranging from exceptional weed control with no damage to the sesame to little or no sesame stand (Grichar & Dotray, 2007). Poor sesame stands with the use of pendimethalin or trifluralin have resulted from incorporating either of the herbicides too deep. Since sesame is planted shallow, it is difficult to properly incorporate the dinitroaniline herbicides effectively and not have the herbicides come in contact with the sesame seed or roots (Grichar & Dotray, 2007).

It is important to realize that the many preemergence herbicides reduce sesame populations, but in mechanized sesame growing, this reduction is not noticed because of the cultural practices. One of the most difficult aspects of growing sesame is getting an uniform stand. The seeds are very small as compared to other field crops such as corn, soybean, cotton, wheat, and peanuts. One of the trends in mechanized agriculture is to singulate the larger seeded crops to attain the optimum plant population. Singulation has not worked in sesame because the seeds need adjacent seeds to help emerge out of the soil. Even with seed that has over 95% germination, rarely do more than 60% of the seeds emerge (Langham et al., 2010). In addition, there are many variations in soil type and row configurations within the sesame growing areas. In order to compensate for poor land preparation, the seeding rate is increased. Sesame varieties have been selected to compensate in high populations by self-thinning and in low populations by branching (Langham 2007). Various studies have shown that the yields are comparable between the untreated check and herbicide treatments that have some stand reduction (unpublished data).

Active ingredient	Preemergence	Postemergence over-the-top	Postemergence directed	Harvest Aid
2,4-DB	Toxic	Toxic		
Acetochlor	Potential	Potential		
Acifluorfen		Toxic	Potential	
Alachlor	Commercial	Potential		
Allidochlor (CDAA)	Mixed results			
Ametryn	Toxic			
Amiprophosmethyl	Toxic			
Asulam	Semi-selective			
Atrazine	Toxic	Toxic		
Benefin	Toxic			
Benfuresate	Toxic			
Bensulide	Selective			
Bentazon		Toxic		
Bifenox		Toxic		
Bromoxynil		Toxic		
Carbuthioate	Semi-toxic			
Carfentrazone			Semi-toxic	Not effective
Chloramben	Mixed results			
Chlorimuron		Toxic		
Chloroxuron	Toxic			
Chlorpropham (CIPC)	Mixed results			
Chlorsulfuron	Mixed results			
Chorthal-dimethyl	Semi-toxic			
Clethodim		Commercial		
Clomazone	Toxic			
Clopyralid	Semi-selective	Toxic		
Cloransulam	Toxic	Toxic		
Dicamba		Toxic		
Dichlobenil	Toxic			
Dichlormate	Semi-selective			
Diclosulam	Toxic	Toxic		
Diethatyl	Semi-selective			
Diethylacetanilide	Semi-selective			
Diflufenican	Semi-toxic	Toxic		
Diflufenzopyr		Toxic		
Dimethenamid	Mixed results			
Dinitramine	Toxic			
Dinoseb	Toxic			
Diphenamid	Selective	Selective		
Diquat				Effective
Diuron	Commercial	Commercial	Potential	
DSMA		Semi-toxic		

Active ingredient	Preemergence	Postemergence over-the-top	Postemergence directed	Harvest Aid
Endothall	Toxic	Toxic		
EPTC	Mixed results			
Ethalfluralin	Mixed results			
Fenoxaprop	Inconclusive			
Fluazifop-P-butyl		Commercial		
Fluchloralin	Commercial			
Flufenacet	Toxic			
Flumetsulam	Toxic	Toxic		
Flumioxazin	Toxic	Semi-toxic	Mixed results	
Fluometuron	Commercial	Semi-selective		
Fluorodifen	Toxic			
Fomesafen		Mixed results		
Glufosinate-ammonium			Mixed results	Effective
Glyphosate	Commercial	Toxic	Mixed results	Effective
Haloxyfop		Selective		
Imazapic	Toxic	Toxic		
Imazethapyr	Semi-selective	Toxic		
Isopropalin	Toxic			
Lactofen		Toxic	Semi-toxic	
Linuron	Commercial	Toxic	Potential	
Mesotrione		Toxic		
Methabenthiazuron		Semi-selective		
Methazole	Mixed results			
Metobromuron	Commercial			
Metolachlor	Commercial			
Metribuzin	Toxic			
Metsulfuron	Mixed results			
Monolinuron	Mixed results			
Monuron	Selective			
MSMA		Semi-toxic		
Napropamide	Mixed results			
Naptalam (NPA)	Toxic	Toxic		
Nicosulfuron	Mixed results	Toxic		
Nitralin	Mixed results			
Nitrofen	Toxic			
Norea	Mixed results			
Norflurazon	Toxic			
Oxadiazon	Semi-selective	Semi-toxic		
Oxasulfuron		Toxic		
Oxyfluorfen	Semi-selective	Toxic		
Paraquat		Toxic	Semi-toxic	Effective
Pebulate	Semi-selective			

Active ingredient	Preemergence	Postemergence over-the-top	Postemergence directed	Harvest Aid
Pendimethalin	Commercial	Potential		
Perfluidone	Selective			
Phenmediphan		Toxic		
Piraflufen ethyl		Semi-selective		
Proatryne	Selective			
Profluralin	Selective			
Prometryn	Toxic	Toxic	Potential	
Pronamide	Toxic			
Propachlor	Selective			
Propanil	Semi-selective			
Propazine	Mixed results	Toxic	Selective	
Prosulfuron	Mixed results	Toxic		
Pyraflufen ethyl		Semi-toxic	Selective	Not effective
Pyridate		Mixed results		
Pyrithiobac	Toxic	Toxic	Toxic	
Rimsulfuron	Selective	Toxic		
Sesone	Mixed results			
Sethoxydim		Commercial		
Simazine	Toxic			
S-metolachlor	Commercial	Potential		
Sufentrazone	Toxic			
Sulfonamide	Mixed results			
Thiobencarb	Toxic			
Triasulfuron	Mixed results			
Trifloxysulfuron	Mixed results	Toxic	Toxic	
Trifluralin	Commercial	Mixed results		
Vernolate	Toxic			

[a]In the evaluation the following categories of effectiveness are used:
Commercial: used commercially in at least one country
Potential: potential to use commercially
Selective to sesame: does not damage sesame
Semi- selective to sesame: some damage to sesame, but helps
Mixed results with some showing some selectivity and others showing toxicity
Toxic: substantial reduction of production
Semi- toxic: enough reduction that probably cannot be used
Effective as a harvest aid
Not effective as a harvest aid

Table 2. Summary of herbicides that have been evaluated for weed control and sesame tolerance[a].

Until 2000, little or no research has been done on the use of postemergence herbicides in sesame (Grichar et al., 2001b). Most of the herbicide work has been at crop establishment. From initial work done in the U.S. in Arizona, several postemergence herbicides have done a very good job controlling grasses and not damaging the sesame. Grass herbicides, fluazifop-P-butyl, haloxyfop, and sethoxydim have been used successfully in many parts of the world. More recently, clethodim has proven equally good controlling both annual and perennial grasses (particularly johnsongrass) and not damaging sesame (Grichar et al., 2001b). There is a label in the U.S. for clethodim (Select Max®) use in sesame which allows spraying in all phases except flowering (Langham et al., 2010). Concerns have been raised on the use of clethodim after extensive glyphosate applications and improper clean-out of spray tanks. Sesame capsule inhibition has been noted when glyphosate carryover has been noted in spray tanks that have been used to apply clethodim. The cleaning and removal of any glyphosate residues in spray tanks after each herbicide use is essential to prevent herbicide carryover.

To date there is no postemergence over-the-top broadleaf herbicide that will control the weeds without damaging the sesame (Grichar et al., 2001b). There are products such as alachlor and metolachlor that cause minimum injury to sesame when applied postemergence, will not control emerged weeds, but will provide some soil residual activity (Grichar et al., 2001a; Grichar et al., 2009). In the case of herbicides such as diuron, sesame will recover, but the farmer will notice stunting and leaf necrosis on sesame leaves for about 10 days after herbicide application (Grichar et al., 2009). In some sesame herbicide research, severe sesame plant stunting and leaf necrosis has resulted in good weed control and produced higher yields than the untreated check because of the loss of production to weeds in the untreated check (Grichar et al., 2009). A controversial use of herbicides is what is known as a "rescue treatment", which is using a herbicide that will injure the sesame, but will bring weeds under some control and allow the sesame to be harvested at an economic return. As an example, a farmer used clopyralid on a portion of a field that was being overwhelmed by common cocklebur (*Xanthium strumarium* L.). Where he did not spray, he lost the crop; however, where he sprayed there was damage to the sesame with control of the cocklebur and he harvested about 660 kg/ha. However, many sesame growers in the U.S. are not tolerant of any type of sesame herbicide injury even knowing that the sesame will recover.

Starting in 2003, research has been conducted using postemergence-directed herbicides with and without the use of hooded sprayers. This work is very encouraging; however, there are many cropping patterns that preclude the use of hooded sprayers. There is a label for glyphosate (Roundup Max®) that allows wiper applicators or hooded sprayers to be used between sesame rows (Langham et al., 2010). While this does not provide effective weed control in the sesame seed row, it helps with vining weeds such as morningglory species (*Ipomoea* spp.) and smellmelon (*Cucumis melo* L.) that spread across the rows. While morningglory is becoming increasingly tolerant of glyphosate, glyphosate will slow the growth of morningglory and reduce the damage to the sesame from this weed. In the case of *Amaranthus*, which quickly can become taller than the sesame, wiper applicators using glyphosate have been very successful, particularly in areas with high relative humidity, as long as the glyphosate does not drip on the sesame. Initial work with spraying glyphosate on the sesame stem showed little injury; however, in subsequent studies, there have been instances of severe damage. In further observations, when the sesame was under moisture stress, there was little damage, but when the plants were in a rapid growth phase following rainfall or irrigation.

One of the major problems in using postemergence-directed herbicides has been the timing of the application and the height of the spray application on the sesame stem as related to the height of the plant. Recent work has shown that there are differences in applying herbicides at

5 cm above the surface versus 15 cm; differences in applying 4 weeks after planting versus 6 weeks; and differences is the heights of the plants in different locations in a field. In waiting for the sesame to get tall enough to spray a postemergence-directed herbicide, weeds also become tall and herbicides may not control taller weeds (Langham et al., 2010).

In reviewing research using postemergence herbicides, it is sometimes difficult to understand exactly at what stage of growth the herbicide was applied (Langham et al. 2007). Many of the documents will cite the number of days after planting or the height of the plants. However, there are many differences in the cultivars of the world in terms of number of days in each stage and in the heights of the plants in each stage as shown in Table 3.

In order to standardize terminology, a phenology chart has been developed to specify the beginning and end points of the stages (Langham, 2007). Table 4 summarizes sesame phenology.

	Days from planting		Phase length	
Phase	Range	Mean	Range	Mean
Vegetative	29-59	42	29-59	42
Reproductive	56-116	89	16-70	47
Ripening	77-140	108	(14)[b]-54	11
Drying	102-181	150	11-57	38

[a] Based on sesame germplasm from Sesaco Corporation (Langham 2007)
[b] In some cultivars, there are dry capsules above green leaves while the upper portion of the plant is still flowering creating a negative range.

Table 3. Range and mean of number of days in phases for sesame germplasm.[a]

Stage/Phase	End point of stage	DAP[a]	No. weeks
Vegetative			
Germination	Emergence	0-5	1-
Seedling	3rd pair true leaf length=2nd	6-25	3-
Juvenile	First buds	26-37	1+
Pre-reproductive	50% open flowers	38-44	1-
Reproductive			
Early bloom	5 node pair of capsules	45-52	1
Mid bloom	Branches/minor plants stop flowering	53-81	4
Late bloom	90% of plants with no open flowers	82-90	1+
Ripening	Physiological maturity	91-106	2+
Drying			
Full maturity	All seed mature	107-112	1-
Initial drydown	1st dry capsules	113-126	2
Late drydown	Full drydown	127-146	3

[a] DAP, days after planting. These numbers are based on S26 (Sesaco Corp.) in 2004 near Uvalde, TX under irrigation.

Table 4. Phases and/or stages of sesame.

Future work on sesame herbicides should specify the stage of the sesame. Recent application timing work has shown that some herbicides are phytotoxic in the seedling stage, are neutral in the juvenile stage, and reduce yield in the pre-reproductive through mid bloom stages. Additional work is needed to verify these initial findings as to the exact neutral stages, but there is enough data to know that plant stage at application is critical.

A second problem in reviewing the literature is that some of the work has not been carried through to completion of the sesame crop (Langham et al. 2007). Sesame has a remarkable ability to compensate. Recent work has compared the stunting/damage ratings of some contact-based herbicides and showed that the amount of damage to sesame was reduced over time and the yields of stunted/damaged materials was comparable to the weed-free checks. Sesame injury ratings should only be done by researchers familiar with sesame. Sesame yields are related to the number of capsules and the seed weight per capsule per square meter. There have been herbicide treatments that apparently damage the sesame, i.e., the yellow splotching of leaves by such herbicides as diuron, but the number and weight of the capsules were not affected. In some cases, the herbicide delayed flowering, but the plants flowered longer. A reduction in plant height may not affect yield.

Below is a discussion of the most promising and effective herbicides for use across the sesame growing areas of the world. A discussion of research in various sesame growing areas is also included.

3. Alachlor

Alachlor, a chloroacetamide herbicide, has been widely used in corn, groundnut, snap bean (*Phaseolus vulgaris* L.), and soybean for preemergence annual grass and broadleaf weed control (Wilson et al., 1988). Bijanzadeh and Ghadiri (2006) reported that alachlor alone controlled redroot pigweed (*Amaranthus retroflexus* L.) 68 to 72% in one year and at least 92% in another, but the efficacy of atrazine plus alachlor increased when tank-mixed together.

Alachlor is the most widely used sesame herbicide in the world. However, little work has been done in the U.S. because the Environmental Protection Agency (EPA) has indicated that additional uses of alachlor would not be approved due to groundwater concerns. Commercial preemergence uses of alachlor include the following: in Thailand, a field guide recommends alachlor at 1.2 to 1.5 L/ha in case of labor shortage (Anonymous, 1997). In Honduras, a grower guide states that alachlor proved to be very effective in the control of weeds in sesame (Anonymous, 2002). In Mexico, a grower guide for Michoacan recommends the use alachlor as a preemergence alone or in combination with linuron and diuron. In all instances, 250 to 300L of water was used as carrier volume (Anonymous, 2007a). In El Salvador, a growers guide recommends 2.8 L/ha of alachlor (Anonymous, 2007b).

Research on alachlor use in sesame dates back 40 years. In Bulgaria, Lyubenov and Kostadinov (1970) conducted experiments with sesame sown on Chernozem Smolnitsa soil. Alachlor applied preemergence at 4 kg/ha effectively controlled weeds and increased sesame seed yields and seed oil content. In Ethiopia, Moore (1973a; 1973b) found that alachlor between 1.6 and 2.9 kg/ha was the safest of the herbicides to be tested, provided high yields, but residual activity was poor. In California, in studies with alachlor applied preplant incorporated under furrow irrigation in multiple locations and years, alachlor provided excellent weed control of *Amaranthus* spp., wild mustard (*Brassica kaber* L.) and various grasses with minimal injury to the sesame, but little control of volunteer barley (*Hordeum vulgare* L.) and marginal control of other broadleaf weeds was noted (St. Andre, unpublished data). In the only experiment carried to maturity, sesame yield following alachlor at 2.25 kg/ha was 1,051 kg/ha, while yields from the weedy and weed-free control

were 259 and 1,075 kg/ha, respectively (St Andre, unpublished data). In India, Subramanian and Sankaran (1977, 1981) conducted experiments over 4 seasons in both summer and winter crops to study the efficiency of alachlor. They found that alachlor at 1.75 kg/ha controlled desert horse purslane (*Trianthema portulacastrum* L.) and purple nutsedge (*Cyperus rotundus* L.) and provided the maximum net income and the highest return per rupee invested in weed control. Graph et al., (1985) showed preemergence treatments with 1.0 to 2.0 kg/ha of alachlor did not injure sesame but caused damage when applied with a preplant incorporated trifluralin treatment. In Australia, Schrodter and Rawson (1984) evaluated alachlor in 3 experiments over two years. They concluded that alachlor was the safest herbicide with yield, population, and vigor similar to the weed-free control. The overall conclusion was that alachlor at 2.25 kg/ha applied preemergence was the most acceptable herbicide treatment for sesame. In Ethiopia, work with various herbicides indicated that the greatest yields were obtained with alachlor at 2.9 kg/ha (Anonymous, 1973). Kim et al., (1986) conducted field trials in the sesame-producing uplands of Korea, to study herbicide efficacy and phytotoxicity in crops grown under polyethylene film. Alachlor at 1.5 L/ha produced sesame yields equivalent to that obtained with manual weed control. In Venezuela, Pineda et al., (1988) tried alachlor as a preemergence herbicide and found it was comparable to the untreated check with respect to sesame yield. In India, Bansode and Shelke (1991) assessed six weed control treatments (an unweeded control, hand-weeding plus hoeing 3 weeks after sowing), and alachlor at 0.75 or 1.5 L/ha applied preemergence in field trials during the kharif of 1988 with sesame cv. Punjab-1 and T-85. Alachlor applied preemergence to cv. Punjab-1 combined with hand-weeding plus hoeing provided greatest yields (689 kg) compared to hand-weeding plus hoeing alone (583 kg) and all other treatments.
In a Venezuela grower guide, Caraballo et al., (1986) found that alachlor applied at 6, 5, 4, and 3 L/ha yielded 1,008, 833, 848, and 810 kg/ha, respectively, compared to the weedy check yield of 536 kg/ha and weed-free check yield of 1,042 kg/ha. In India, Dungaral et al., (2003) conducted a field experiment during the kharif seasons of 1997 and 1998 to evaluate the relative efficacy of alachlor applied alone or in combination with one hoeing at four weeks after sowing to control weeds in sesame cv. TC 25. On average, season-long weed competition caused 50% reduction in seed yield. Among the herbicides, the preemergence application of alachlor at 2.0 kg/ha combined with one hoeing at 4 weeks after sowing registered the greatest weed control efficiency, which enhanced yield attributes leading to greater seed yield (530 kg/ha) and net return (Rs. 4275/ha). In India, Anil and Thakur (2005) concluded that the greatest sesame yields were obtained with alachlor at 1.5 kg/ha alone or in combination with hand weeding. In the U.S., B. Sadler (2007, personal communication) has grown sesame for bird hunting for the past twenty years. He has used both alachlor and metolachlor in alternating years in order to control yellow (*Cyperus esculentus* L.) and suppress purple nutsedge.

4. Metolachlor and *S*-metolachlor

Metolachlor or *S*-metolachlor are commonly used in various crops for control of small-seeded broadleaf weeds, some annual grasses, and yellow nutsedge (Grichar et al., 1996). *S*-metolachlor will control small-seeded annual grasses, but does provide inconsistent control of large-seeded annual grasses (Grichar et al., 2004a; 2004b). Many growers have reported peanut stunting when soil applications of metolachlor have been followed by rain (Grichar et al., 1996). Grichar et al., (1996) reported that postemergence applications of metolachlor followed by irrigation within 24 h could be effective for yellow nutsedge control and reduce the chance of peanut injury from soil applications. Combinations of factors, such as herbicide dose, moisture conditions at planting, soil organic matter, and pH may affect peanut injury by chloroacetamide herbicides such as *S*-metolachlor (Cardina & Swann, 1988; Wehtje et al., 1988; Osborne et al., 1995; Mueller et al., 1999). Cardina and Swann (1988) reported that metolachlor often delayed peanut emergence and reduced peanut growth when irrigation followed planting; however, yield loss was observed only when metolachlor was applied at a 3X rate.

In many areas of the world, metolachlor has shown similar results as alachlor on sesame and is being used more frequently because it requires less active ingredient per hectare to achieve similar results. Commercial preemergence uses of metolachlor include the following: in Thailand, a field guide recommends metolachlor at 1.2 to 1.25 L/ha in case of labor shortage (Anonymous, 1997). In Australia, grower guides in the Northern Territories (Bennett 1998) and in South Burnett (Sapin et al., 2000) recommend the use of metolachlor. In El Salvador, a grower guide recommends 1.4 L/ha of metolachlor (Anonymous, 2007c). Reportely, alachlor has been used in commercial fields in Mexico, Venezuela, Brazil, Nigeria, Ethiopia, Nicaragua, Guatemala, and Argentina.

In preemergence experiments in the U.S., metolachlor treatments (2.2 kg/ha) had a slight reduction in sesame vigor, provided good broadleaf control initially, but allowed broadleaf weeds to germinate later (St Andre, unpublished data). Metolachlor applied preemergence at 2.1 kg/ha was one of the best overall treatments, but preplant incorporation of metolachlor affected early vigor and stunted the sesame (D. Howell, unpublished data). In Egypt, metolachlor alone at 1.2 and 1.8 kg/ha and a premix of metolachlor and metobromuron (Galex®) was tested. The premix provided good broadleaf weed control while both metolachlor alone and the premix provided good annual grass control (Hussein et al., 1983). In Nicaragua, metolachlor at 1.1 and 2.2 kg/ha provided good grass control, did not injure the sesame, and doubled the yield from that of the untreated check (Soto-Soto & Silva-Vasquez, 1987). In Ethiopia, metolachlor at 1.7 kg/ha provided good grass and broadleaf control, which resulted in a significant yield increase (Zewdie, 1994). In Australia, Martin (1995) reported that metolachlor adequately controlled weeds but caused unacceptable crop injury. Despite that report, farmers use metolachlor for commercial sesame fields (M. Bennett, L. Serafin, and P. O'Shanesy, personal communication). Metolachlor at 0.6, 1.1, 2.2, and 3.4 kg/ha resulted in variable sesame plant populations, had no effect on sesame plant height, resulted in consistent weed control, and provided greater yields than the untreated plots (Grichar et al., 2001a).

In later work at a south Texas location, *S*-metolachlor caused no sesame stand reduction or injury; however, at the Lubbock location, stand reduction and injury was noted in one of two years (Grichar et al., 2009). Also, sesame stand reductions have been observed in Oklahoma where *S*-metolachlor was applied followed by irrigation, but there was no problem when planted into moisture (C. Medlin & C. Godsey, personal communication). However, in 2009, there was no stand reduction (J. Armstrong, personal communication). In Argentina, metolachlor at 0.8 kg/ha provided good control of *Amaranthus quitensis* but marginal control of *Raphanus sativus*. *S*-metolachlor did provide similar yields to the weedy and weed-free checks (L. Lanfranconi, unpublished data). *S*-metolachlor alone in comparison with diuron, linuron, and a premix of linuron and diuron has produced sesame yield similar to the weed-free check at several location in Texas (Table 5). When *S*-metolachlor was applied postemergence over-the-top of sesame at the juvenile stage, minimal stunting and yield differences were observed (authors' personal observations).

		Lorenzo		Uvalde [a]	Average yield vs. untreated
Treatment	Rate	2007	2008	2008	
	Kg ai/ha	Kg/ha			Percent
Untreated		1,224	763	1,233	100
Diuron	0.6	1,417	835	1,127	106
Diuron	1.2	1,350	751	1,211	102
Diuron	2.4	1,215	742	1,105	95
Linuron	0.6	1,280	829	1,199	103
Linuron	1.2	1,278	879	1,300	108
Linuron	2.4	1,267	625	1,289	97
S-metolachlor	0.7	1,168	773	1,233	99
S-metolachlor	1.4	1,138	834	1,161	99
S-metolachlor	2.8	1,185	888	1,237	105
Linuron + diuron	0.3 + 0.3	1,203	790	1,199	100
Linuron + diuron	0.6 + 0.6	1,327	767	1,121	100
Linuron + diuron	1.1 + 1.1	1,374	781	1,239	105
LSD (0.05)		NS	140	NS	
[a] No yield taken in 2007 due to glyphosate drift from adjacent sorghum fields.					

Table 5. Sesame yield response to preemergence herbicides at two locations in Texas.

In the U.S., *S*-metolachlor has been used under temporary labels from the EPA on over 50,000 hectares of sesame and provided good weed control with no evidence of a reduction in yield. Hundreds of hectares that have not had *S*-metolachlor applied have been plowed under because of severe weed pressure. *Amaranthus spp*. and small-seeded grasses are the most damaging weeds to sesame in the U.S. and *S*-metolachlor provides excellent control of these weeds when applied immediately after planting of sesame (Grichar et al., 2001a; 2009).

5. Diuron

Diuron is systemic urea herbicide that inhibits photosynthesis and has been used to control various weeds in cotton (Culpepper et al., 2004). Reddy et al., (2007) reported that ragweed parthnium (*Parthenium hysterophorus* L.) was highly sensitive to pigment inhibitors and photosynthetic inhibitors such as diuron compared to herbicides with other modes of action. Commercial preemergence uses of diuron in sesame include the following: in Mexico, a grower guide recommends a diuron mixture with alachlor at 0.5 kg plus 1.0 kg/ha, respectively, for commercial fields (Anonymous, 2007a). Diuron, when used preemergence, controls many broadleaf weeds that cannot be controlled by *S*-metolachlor. Also, diuron has the potential to be used postemergence as a rescue treatment when broadleaf weeds are growing profusely.

In preemergence experiments in Venezuela, diuron at 0.6 and 1.2 kg/ha reduced sesame yield, but yield would have been much lower without weed control (Mazzani, 1957). In one year in the U.S., diuron at 0.8 and 1.7 kg/ha resulted in adequate weed control without apparent crop injury; however, in another year, there was stand reduction and chlorosis (Culp & McWhorter, 1959). Further work in Venezuela showed that diuron provided reasonable control of weeds with no significant reduction in yield (Montilla, 1964; Mazzani, 1966). In Sri Lanka, diuron at 0.6 and 0.8 kg/ha effectively controlled weeds with no significant reduction in yield (Appendurai, 1967); however in Ethiopia, diuron caused serious crop damage in both irrigated and rainfed trials (Moore, 1974). In Egypt, diuron at 1.0 kg/ha was tested alone and in tank mixtures with pendimethalin. The herbicide combinations controlled both grass and broadleaf weeds and resulted in greater yields (Ibrahim et al., 1988). In contrast, Viera et al., (1998) reported that diuron mixtures (0.8, 1.0, and 1.3 kg/ha) with pendimethalin and alachlor caused greater phytotoxicity with the greatest dose. However, there was no difference in the height of the first fruiting branch, the number of capsules per plant, and the yield between the different herbicide treatments and manual weeding (Viera et al., 1998). In Brazil, diuron at 1.0 kg/ha enhanced seed production (Beltrao et al., 1991). In later work by Grichar et al., (2009), they reported that diuron at 1.12 kg/ha reduced sesame stands and caused sesame injury in one year in the Texas High Plains area; however, in south Texas no adverse effects with diuron were seen in the two years. Sesame yield from plots treated with diuron have not been different from the weed-free check (Table 5).

Diuron also has a potential for use as a postemergence both over- the-top and directed. In post-directed studies, the authors have found that diuron controls emerged weeds with minimal damage to the sesame. In Venezuela a grower guide (Avila, 1999) recommends that when the plants are about 30 cm tall [juvenile stage], diuron should be used at 1.5 L/ha. They reported that diuron controlled the weeds with minimum damage to the sesame. In Venezuela, Caraballo (1986) did a timing study using diuron at 1.5 L/ha with 0.5 L of surfactant. Applications at 15, 22, 29, 36, 43, and 50 days after planting resulted in yields of 947, 896, 817, 911, 762, and 770 kg/ha, respectively, compared to 557 kg/ha in the weedy check and 1117 kg/ha in the hand-weeded check. Diuron controlled 94% of the broadleaves and 89% of the grasses.

In recent work with postemergence applications of diuron, an application at the late juvenile stage has shown a discoloration of the leaves and some height reduction, but yields have been comparable to the weed-free check (authors' personal observations). Recent timing studies have shown that time of application is critical. Minimal sesame damage has been found when diuron has been applied in the late juvenile stage; however, earlier applications in the seedling stage severely damaged the sesame and applications during sesame flowering reduced yield (authors' personal observations).

6. Linuron

Linuron, a substituted urea herbicide, has been used extensively in cotton and carrot (*Daucus carota* L.) as a preemergence or postemergence herbicide since the 1960's for control of annual broadleaf weeds such as pigweed spp., common ragweed (*Ambrosia artemisiifolia* L.), common groundsel (*Senecio vulgaris* L.), and common purslane (*Portulaca oleracea* L.) (Bell et al., 2000; Bellinder et al., 1997; Saint-Louis et al., 2005). Linuron can be used in combination with 2,4-DB to control sicklepod (*Cassia obtusifolia* L.) in soybean; however, a height differential must be established between soybean and sicklepod to cover the weeds without contacting more than the lower 25 to 30% of the soybean plant to reduced herbicide injury (Shaw & Coats, 1988).

Commercial preemergence uses of linuron in sesame include its use in Mexico. A grower guide recommends a linuron mixture with alachlor at 0.5 kg plus 1.5 L/ha, respectively, for commercial fields (Anonymous, 2007a).

In studies using linuron applied preemergence, Santelmann et al. (1963) found slight phytotoxicity and a reduction in sesame yield with linuron at 2.24 kg/ha. In Bulgaria, Lyubenov and Kostadinov (1970) found preemergence application of mixtures of 3 kg/ha of linuron and 3 kg/ha of alachlor gave effective control of weeds and increased seed yields and seed oil content. In Egypt, Hussein et al. (1983) found linuron at 1.8 kg/ha increased the seed yield 60% as compared to the weedy check. Seed oil content was not affected. In Australia, Schrodter and Rawson (1984) evaluated linuron in 3 experiments over two years. They concluded that linuron increased the yield over the weedy check, but did not provide yields comparable to alachlor and the weed-free control. In Nicaragua, Soto-Soto & Silva-Vasquez (1987) conducted trials in two sites. They concluded that linuron provided the best control of broadleaf weeds and metolachlor provided the best control of grasses; neither damaged the sesame; and recommended rates of 2.1 L/ha for both herbicides. In Argentina, linuron applied preemergence at 1.5 and 2.0 L/ha controlled weeds and provided yields close to the check (L. Lanfranconi, unpublished data). In the U.S., linuron at 0.6 to 2.4 kg/ha has produced yields as good as the weed-free check (Table 5).

Linuron in combination with glyphosate as a postemergence-directed spray has caused severe sesame injury. In more recent work, however, linuron alone did not injure sesame and controlled problem weeds such as morningglory and smellmelon. Linuron can complement the use of metolachlor by providing additional broadleaf weed control.

7. Fluometuron

Fluometuron controls many annual dicotyledon weeds, however, it does not completely control some of the more troublesome weeds found in crops such as cotton (Burke & Wilcut, 2004). These troublesome weeds that fluometuron does not completely control include *Amaranthus* spp., *Ipomoea* spp., prickly sida (*Sida spinosa* L.), and sicklepod (*Senna obtusifolia* L.) (Buchanan, 1992; Crowley et al., 1979; Culpepper & York, 1997). Fluometuron applied postemergence may injure cotton and delay maturity (Guthrie & York, 1989). Guthrie and York (1989) stated that growers may resort to this type of application when an insufficient height differential between the crop and weeds prohibits postemergence-directed herbicide applications. Commercial preemergence uses of fluometuron in sesame include Costa Rica, where a grower guide (Anonymous, 2007d) recommends using an application of fluometuron at 2 kg/ha.

In preemergence experiments in India, fluometuron did not perform as well as alachlor or dichlormate (Subramanian & Sankaran, 1977). In Bulgaria, fluometuron at 1.0 kg/ha applied 2 days after sowing controlled annual broadleaf weeds. The quality and fat content of sesame seeds were not affected (Georgiev, 1980). In India, Subrananian & Sankaran (1981) found that fluometuron at 0.25 to 1.75 kg/ha did not perform as well as alachlor. In the U.S., fluometuron rates of 0.3 and 1.1 kg/ha had no effect on sesame height or population, provided good weed control, and had comparable yields to the check in south Texas (Grichar et al., 2001a). Later, Grichar et al., (2009) reported that fluometuron at 1.12 kg/ha in the High Plains region of Texas reduced sesame stand and caused injury in one of two years while no stand reduction or injury was noted at the south Texas location.

Recent work has evaluated fluometuron for use as a postemergence herbicide. There is some damage to the sesame when applied postemergence; however, it may be a good rescue herbicide. The sesame damage parallels diuron in that there is less damage in the late juvenile stage.

8. Prometryn

Prometryn has been widely used as a residual soil-applied and postemergence-directed herbicide in cotton grown west of the Mississippi River in the U.S. (Byrd, 2000) and controls many annual grasses and broadleaf weeds (Corbett et al., 2002; Burke & Wilcut, 2004). Prometryn is the only registered herbicide in the U.S. that provides excellent broad-spectrum control of weeds such as little mallow (*Malva parviflora* L.), shepherdspurse (*Capsella bursa-pastoris* L.), common purslane (*Portulaca oleracea* L.), and burning nettle (*Urtica urens* L.) in celery (*Apium graveolus* L.) (Daugovish et al., 2007). Currently, there is no commercial use of prometryn in sesame.

In preemergence experiments in Ethiopia, prometryn at 1.0 kg/ha was used safely on irrigated sesame while prometryn at 1.85 kg/ha resulted in less than 10% sesame injury. In a similar trial under natural rainfall, prometryn at 2.2 kg/ha completely eliminated the crop (Anonymous, 1973). In other studies in Ethiopia under irrigated conditions, prometryn applied preemergence at 3.2 kg/ha provided excellent weed control with negligible crop damage. However, under rain-fed conditions, prometryn at 0.8 kg/ha caused 100% sesame mortality (Moore, 1974). In Egypt, prometryn at 1.9 kg/ha caused sesame injury compared to pendimethalin alone and in tank mixtures with linuron and diuron (Ibrahim et al., 1988). In the U.S., preemergence applications of prometryn at 0.5 kg/ha caused no sesame injury, but prometryn applied preplant incorporated almost completely eliminated the sesame (D. Howell, unpublished data). Prometryn at 0.6 and 1.1 kg/ha resulted in lower sesame populations, lowered plant height, and also significantly reduced yields compared with metolachlor at 1.1 or 2.2 kg/ha (Grichar et al., 2001a). However, in a later study in south Texas and the High Plains of Texas, prometryn injured sesame but yields were not reduced from that of *S*-metolachlor (Grichar et al., 2009).

Farmer experience with prometryn is instructive in how a simple change in planting procedures can change results dramatically. In Arizona in the early 1980s, prometryn applied preplant incorporated provided excellent weed control with no apparent damage to sesame. In one year, suddenly there were very poor stands. In analyzing the situation, the farming practices had been to use a double disc opener to open the soil followed by press wheels after the seed was planted to close the gap. Farmers had decided that at times the press wheels did not close the trench resulting in moisture loss and poor germination. A few farmers put a chain on the back of each planter unit to drag soil back over the trench. These were the farmers that were not getting a stand. Basically, the double disc openers were pushing the soil layer with the prometryn to the sides, and allowed the sesame to germinate through the prometryn-treated herbicide zone. With the new farming practice, the soil with prometryn was brought back over the seed, and the sesame would not germinate. One simple farming practice changed success to failure.

In the past few years in Texas, under some conditions, prometryn applied preemergence has caused severe injury while in other instances little or no sesame injury has been noted. Another concern with prometryn is the effect on the sesame when the herbicide is applied to the previous crop. In West Texas, it is common to have localized hail storms that destroy cotton fields. In many cases, it is too late to replant cotton, but early enough to plant sesame. Sesame has followed thousands of hectares of failed cotton treated with prometryn with little or no injury to the sesame.

In studies with prometryn applied postemergence over-the-top or postemergence-directed, no injury has been noted with prometryn applied postemergence-directed but severe sesame injury has been found when applied over-the-top (author's personal observations). Excellent weed control, especially morningglory spp., has been noted with the postemergence-directed applications.

9. Clethodim, Fluazifop-P-butyl, Sethoxydim and Haloxyfop

Large seed grasses such as Texas millet [*Urochloa texana* (Buckl.) R. Webster] and rhizome johnsongrass can be a serious problem in sesame fields and are not controlled with current preemergence herbicides; therefore, postemergence grass herbicides are an absolute necessity. Postemergence control of annual grasses can be obtained with several herbicides (Grichar, 1991 a,b; Prostko et al., 2001). Grichar (1991a) found that sethoxydim applied early postemergence provided more effective annual grass control than late postemergence applications. However, grass size did not affect control with clethodim. Sethoxydim was reported to provide poor Texas millet control under less than ideal moisture conditions (Grichar, 1991a). Grichar (1991a) speculated that reduced moisture conditions resulted in less uptake and translocation of the herbicide within the plant (Chernicky et al., 1984; Fawcett et al., 1987). Clethodim controls annual grasses at lower use rates than sethoxydim. Prostko et al. (2001) noted 90% Texas millet, southern crabgrass (*Digitaria ciliaris* L.), or crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.] control occurred when clethodim followed an application of a soil applied dinitroaniline herbicide.

Commercial postemergence uses of grass herbicides in sesame include the following: in a Venezuela grower guide (Avila, 1999) stated that for grasses, fluazifop-P-butyl at 200 to 400 ml/ha worked well. In Australia, a grower guide (Sapin et al., 2000) stated that sesame was susceptible but tolerated fluazifop-P-butyl, haloxyfop, and sethoxydim. In Nigeria, a survey of agricultural crops (Anonymous, 2004a) suggested that fluazifop-P-butyl was used by two sesame farmer cooperatives. In the U.S., a producer guide (Langham et al., 2010) states that there is a label for clethodim but it should not be used during the flowering phase. Clethodim use during flowering will prevent capsule formation for 1 to 10 node pairs. Reportedly, fluazifop-P-butyl is commercially used in Mexico, Guatemala, Brazil, Paraguay, and Argentina while sethoxydim is used in Australia, and clethodim is used in the U.S.

In studies in Somalia, Malik and Muhammed-Ramzan (1992) showed that fluazifop-P-butyl at 3.7 L/ha and hand weeding provided effective control of grasses. In the U.S., Grichar et al., (2001b) reported that fluazifop-P-butyl and sethoxydim increased sesame yield over the untreated check and this was attributed to the control of Texas millet and southern crabgrass. In field studies in south Texas, clethodim has had no effect on sesame; however, when used by growers there has been considerable sesame injury under certain conditions. This injury has manifested itself as an inhibition of capsule formation. Field experiments which tried to replicate farmer results by using every permutation of 1x, 2x, and 3x rates of clethodim and 0, 1x, 2x, and 3x rates of crop oil showed no damage to sesame. However, in 2005, minute traces of glyphosate were added to clethodim and the farmer results were replicated. It was hypothesized that glyphosate residues had contaminated the clethodim in commercial air and ground sprayers. Further analysis of the effects of glyphosate drift from adjacent fields showed the same symptoms of yellowing of the growing tip, poor growth, and lack of formation of capsules for a period of time. Additional testing of timing of clethodim applications has shown that certain conditions, the application of clethodim during flowering will result in no capsule formation for 0 to 10 node pairs. However, there is not yellowing of the growing tip and plant growth is normal. Minimal damage to sesame (in the form of lack of capsule formation) has been noted with fluazifop-P-butyl and sethoxydim.

10. Glyphosate and/or Glufosinate-ammonium

Glyphosate is one of the safest and most frequently used herbicides in the world (Tao et al., 2007). It is a non-selective herbicide that controls many weed species. Products containing glyphosate are registered in more than 130 countries and are approved for weed control in more than 100 crops (Fernandez-Cornejo & McBride, 2000). Use of glyphosate increased dramatically with the introduction of glyphosate resistant crops. Crops that are glyphosate resistant allow glyphosate to be used as a selective herbicide and have offered additional options for weed control and have brought tremendous economic and agronomic benefits to growers around the world (Prostko et al., 2003; Thomas et al., 2006). A weakness of glyphosate is poor morningglory control (Corbett et al., 2004; Jordan et al., 1997).

Another development from the use of glyphosate-tolerant (Roundup Ready®) crops has been, in some instances, reduced weed pressure or increased weed species shifts when a Roundup Ready® crop has been grown for a number of years (Culpepper et al., 2000; Hilgenfeld et al., 2004; Marshall et al., 2000). In these areas, glyphosate has been so effective at controlling weeds that farmers are not concerned with a build-up of weed seed in the soil. Also, the overuse of this herbicide has resulted in an increase in glyphosate resistance to several weed species including *Amaranthus* spp., Italian ryegrass (*Lolium multiflorum* L.), and marestail or horseweed (*Conyza canadensis L. Cronquist*) (Bradshaw et al., 1997; Culpepper et al., 2006; Feng et al., 2004; Koger and Reedy, 2005; Mueller et al., 2003; Peterson, 1999).

Glyphosate is cleared in the U.S. for use in sesame as a burndown, with wiper applicators, and/or hooded sprayers in row middles (Langham et al., 2010). For burndown use, glyphosate should be applied before, during, or just after planting but before the sesame seedlings emerge. There have been no reports of glyphosate damage with the exception of late application where the seedlings have cracked the ground and exposed the plant to direct contact with the glyphosate. In the commercial use of glyphosate between the row middles, many weedy fields have been cleaned of weeds with no damage to the sesame. Wiper applications have been successful in controlling *Amaranthus* spp. as long as there is a height differential between the weeds and sesame with the weeds taller than the sesame. The wipers need to be adjusted throughout the field and careless low wipers that touch the sesame will either kill or severely damage the sesame.

Glyphosate applied postemergence over-the-top to sesame will result in plant death. In commercial fields, aerial recognition mistakes have taken airplanes spraying cotton over sesame fields and have killed sesame. Glyphosate drift from spraying adjacent fields have led to kill or yellowing of the sesame and a lack of capsule formation for one to three weeks depending of the amount of drift (Langham et al., 2010). When capsule formation does somewhat recover, the capsules will be smaller and will have less seeds and seed weight.

In postemergence-directed studies, glyphosate applied up to the 15-cm stem height resulted in 28% stunting; however, when applied to the 5-cm sesame stem height, stunting was no greater than 15% (Grichar, unpublished data). Glyphosate plus diuron stunted sesame 10% when applied up to 15 cm; however, no other herbicides stunted sesame more than 4% when applied to sesame at either height. In 2007, sesame stunting was greater than 2006 and more herbicides caused stunting. Stunting was more severe with glyphosate, glufosinate-ammonium, pyrithiobac, and trifloxysulfuron when applied 15 cm in sesame height compared with applications made 5 cm in height. Only glufosinate-ammonium, pyraflufen-ethyl, diuron plus linuron (Layby Pro®), and linuron at 5 cm caused less than 10% sesame stunting (Grichar, unpublished data). However, in subsequent years, all combinations using

glyphosate severely damaged the sesame. Further analysis showed a correlation between stage and condition of the sesame. The older sesame was less susceptible, but the clearest correlation was the amount of stress. When there was severe drought stress, there was less damage than when the plants were rapidly growing after recent irrigations or rains.
Glufosinate-ammonium is a nonselective postemergence herbicide like glyphosate that may have potential for use in sesame in many of the same ways. It controls a wide range of weed species and is especially effective on morningglory that can be difficult to control with glyphosate (Askew et al., 1997; Corbett et al., 2004; Hydrick and Shaw, 1995). Glufosinate-ammonium inhibits the synthesis of glutamine from glutamine and ammonia by inhibiting the activity of glutamine synthesis (Coetzer et al., 2002). This causes accumulation of ammonium and inhibition of photosynthesis (Sauer et al., 1987; Wild & Manderscheid, 1984). Glufosinate-ammonium is degraded rapidly by soil microorganisms (Wauchope et al., 1992). It controls several grasses and broadleaf weeds including *Amaranthus* spp. (Coetzer et al., 2002). Use of glufosinate-ammonium was limited to burndown treatments on noncrop areas and in no-till plantings; however, advances in genetic transformation of plants have facilitated the development of glufosinate-ammonium resistant crops such as corn, cotton, and soybean (Bradley et al., 2000; Coetzer et al., 2002; Wilson et al., 2007).
Postemergence-directed use of glufosinate-ammonium has produced similar results to glyphosate with mixed results ranging from no damage to severe damage. Work with glyphosate and glufosinate-ammonium as postemergence-directed sprays has been abandoned because these herbicides can severely damage the sesame and do not provide any late preemergence activity.

11. Trifluralin and Pendimethalin

The dinitroaniline herbicides, such as trifluralin and pendimethalin, are used to reduce weed populations and aid in the establishment and production of many crops including groundnut, soybean, and grain sorghum (Dotray et al., 2004; Grichar & Colburn, 1993; Grichar et al., 2005a, b; Grichar, 2006). The dinitroaniline herbicides provide excellent control of annual grasses (Buchanan et al., 1982; Chamblee et al., 1982; Wilcut et al., 1995) and are the only soil-applied herbicides registered for use in peanut that will provide full-season control of Texas millet (Wilcut et al., 1987a,b; Wilcut et al., 1995).
Uptake of dinitroaniline herbicides is primarily through roots and emerging shoots (Ashton & Crafts, 1981; Appleby & Valverde, 1989). Parker (1966) showed that trifluralin was more inhibitory to *Sorghum bicolor* when absorbed through roots than emerging shoots. It is possible that the dinitroaniline herbicides will be concentrated in the extreme upper portions of the soil profile and weed seed may be able to germinate below the zone where dinitroaniline herbicides are located (Johnson et al., 2002). In this case, emerging shoots pass through treated soil, whereas developing roots would be below the herbicide treated soil. The dinitroaniline herbicides have very low water solubility and are subject to losses due to photodecomposition and volatilization (Weber, 1990). Therefore, incorporation soon after herbicide application is important for effective weed control.
The effectiveness of soil-applied herbicides is dependent upon several factors, including movement of the herbicide into the soil either through water provided by rainfall or irrigation, or by mechanical incorporation (Prostko et al., 2001; Ross & Lembi, 1999). Chenault et al. (1992) reported that pendimethalin or trifluralin provided greater than 78% control of barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv) depending on incorporation

method. Tolerance to the dinitroaniline herbicides has been evaluated extensively in many crops. These herbicides injure susceptible plants by binding to β-tublin molecules, which ultimately leads to an inhibition of cell mitosis (Appleby & Valverde, 1989). Information on absorption and translocation within plants is less clearly defined; however, direct entry into plant tissue is considered limited, and unless the dinitroaniline herbicide enters meristematic tissues, the herbicide will have little effect on plant growth (Miller et al., 2003).

Previous research by Grichar et al. (2001a; 2009) reported sesame injury following the use of dinitroaniline herbicides applied preplant incorporated using various incorporation methods. Grichar et al. (2001a) reported that ethalfluralin, pendimethalin, and trifluralin reduced sesame stand numbers when compared with the untreated check. In that study the dinitroaniline herbicides were incorporated 2.5 cm deep with a tractor-driven power tiller. In another study, Grichar et al. (2009) reported that a spring-tooth harrow, with the lack of the ability to adjust incorporation depth, caused similar problems. However, the rolling cultivator mixing wheels, which were set to a depth of less than 2.5 cm, resulted in excellent sesame stands. Therefore, only a shallow incorporation of the dinitroaniline herbicides must be done when used in sesame to ensure a good stand. They concluded that it was best if the dinitroaniline herbicides were applied preemergence. Of the dinitroaniline herbicides, only pendimethalin formulated as Prowl $H_20^{®}$ can be applied preemergence (Anonymous 2004b); however, annual grass control following pendimethalin applied preemergence is often poor (Byrd & York, 1987; Culpepper, 1996).

Commercial uses of trifluralin in sesame include: in Honduras, a grower guide (Anonymous, 2002) states that use of trifluralin applied preemergence has proved to be very efficient in the control of weeds in sesame while in Costa Rica, a grower guide (Anonymous, 2007d) recommends using a preemergence application of trifluralin at 2.0 L/ha.

Martin and Crawford (1963) and Martin (1964) reported that trifluralin at 1.1 to 1.8 kg/ha was effective and non-toxic; however, trifluralin at 2.8 kg/ha killed sesame. In Venezuela, Montilla (1964) tried trifluralin at 1, 2, 3 L/ha, and the sesame did not germinate. In Ethiopia, Moore (1974) reported that trifluralin applied preplant incorporated at 0.75 and 1.4 kg/ha provided the greatest yields in sesame. Hussien et al. (1983) reported that trifluralin at rates greater than 0.84 kg/ha was harmful to sesame. However, it controlled annual grasses and increased the yield over the weedy check by 45%. Schrodter and Rawson (1984) reported that pendimethalin at 1.5 and 3.0 kg/ha and trifluralin at 0.84 kg/ha reduced sesame plant populations. Plant selectivity by herbicide placement is influenced greatly by the movement of the herbicide in soils (Ennis, 1964). If the dinitroaniline herbicides move, they may come in contact with the absorptive sites of sesame and cause sesame injury (Grichar et al., 2001a). In India, Shukla (1984) found that pendimethalin was toxic to sesame. In Israel, Graph et al. (1985) reported that preplant incorporation of trifluralin at 0.125 to 0.188 kg/ha was selective to sesame when the crop was sown on relatively warm soil, but early sowing resulted in inhibited root growth, retardation, and crop damage. In Korea, Kim et al. (1986) found that pendimethalin provided effective weed control using 1.27 kg/ha, but caused crop damage and yield reductions. In Egypt, Ibrahim et al. (1988) found that the best weed control and significantly greater seed yields and seed and yield components resulted from treatment with pendimethalin alone or in tank mixtures with linuron or diuron. In Somalia, Malik and Muhammed-Ramzak (1992) reported that pendimethalin at 3.7 L/ha provided the greatest weed control and significantly higher yield over the weedy check with no phytotoxic effects on sesame. Grichar et al. (2001a) reported yield increases over the untreated check with pendimethalin and trifluralin. They concluded that lack of yield differences among herbicide treatments which injured or reduced sesame stands could be attributed to the ability of the sesame plant to compensate for reduced stands. Sesame can produce excellent yields with only six to ten plants/m of row (author's personal observation). The rate of a dinitroaniline herbicide can affect sesame stand establishment. The one-half rate of ethalfluralin, pendimethalin EC, and trifluralin or the 3/4X dose of pendimethalin (Prowl $H_20^{®}$) resulted in greater stand counts than the 1 to 2X rate of these herbicides when incorporated with rolling cultivator mixing wheels (Grichar & Dotray, 2007).

12. Harvest aids

There are four reasons to use a harvest aid: (1) accelerate the drying to allow earlier harvest in better weather conditions (less rainfall, higher temperatures, and longer daylength), (2) create a uniform field where there are differences in moisture (lower areas with more moisture generally mature later) or late germination (seed that is planted in dry soil can germinate as much as 6 weeks later), (3) control weeds to dry down the entire field (green weeds can delay harvest or increase moisture in the combine bin), and (4) stop regrowth after a late rain (sesame can revert from the drying phase to the reproductive phase). Initial results show that use of a dessicant before the sesame drying phase can reduce the yields by as much as 10%. Initial results show that paraquat and diquat dry down the crop faster than any other harvest aid, but they will not kill weeds or stop regrowth. Glyphosate and glufosinate-ammonium take longer to dry down the crop, but do a more thorough job in a uniform drying down.

13. Conclusions

Herbicides are available that can help control weeds during the production of sesame. Control of weeds is the most important part of sesame production. There are millions of non-mechanized and hundreds of thousands of mechanized hectares of sesame grown every year with good economic return and minimum loss to weeds. However, improved weed control systems will contribute to increased net returns of the crop. The strategy that is being considered is to use a preemergence herbicide that has residual control and will provide effective soil residual control for approximately 4 to 6 weeks followed by a postemergence herbicide that will control small weeds and possibly provide residual control of weeds that have not germinated.

In all of the testing, there are few herbicides that do not affect sesame under some conditions; however, it is clear that in weedy conditions, sesame cannot produce economical yields. Therefore, some damage must be acceptable and with this minimal damage to the sesame, many herbicides have produced excellent economic yields. In the 1920s, Iowa farmers used to say that they plant 3 kernels of corn, "One for the worm, one for the crow, and one for me." Perhaps, in this century sesame farmers will need to plant extra sesame seed, "Some for the herbicide, and most for me."

14. References

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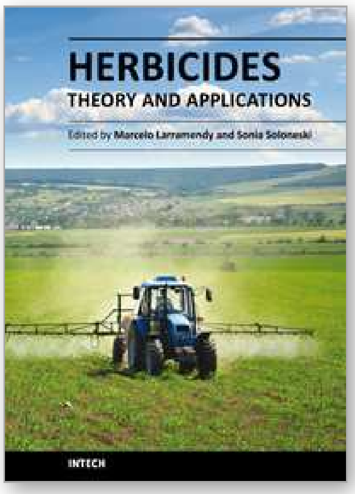

Herbicides, Theory and Applications

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The content selected in Herbicides, Theory and Applications is intended to provide researchers, producers and consumers of herbicides an overview of the latest scientific achievements. Although we are dealing with many diverse and different topics, we have tried to compile this "raw material" into three major sections in search of clarity and order - Weed Control and Crop Management, Analytical Techniques of Herbicide Detection and Herbicide Toxicity and Further Applications. The editors hope that this book will continue to meet the expectations and needs of all interested in the methodology of use of herbicides, weed control as well as problems related to its use, abuse and misuse.

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